CHAPTER

41

Biomass, Energy, and Industrial Uses of Forages

Matt A. Sanderson, *Research Agronomist, Pasture Systems and Watershed Management Research Unit, Agricultural Research Service, USDA, University Park, PA*
Neal P. Martin, *Director, US Dairy Forage Research Center, Agricultural Research Service, Madison, WI*
Paul Adler, *Research Agronomist, Pasture Systems and Watershed Management Research Unit, Agricultural Research Service, USDA, University Park, PA*

Society relies heavily on nonrenewable energy sources such as coal, oil, and natural gas. Shifting from fossil carbon (C) sources to contemporary C sources has been termed a shift to a *bio-based* economy. The discovery of new uses for forages has enhanced the value of these perennial crops beyond their traditional uses for animal feed and conservation. Converting forage plants into biofuels, industrial products, and human-use products has been termed the *biorefinery concept* (Fig. 41.1). Relying on contemporarily fixed-C rather than fossil sources as the feedstock for these new products is a renewable approach.

Biomass generally refers to the organic matter from plants and, in terms of energy production, includes herbaceous and woody crops along with their residues (McKendry, 2002a; Brown, 2003). Biofuels derived from this organic matter include alcohols, ethers, esters, and other chemicals. The term *biofuels* often is used interchangeably when referring to fuels for electricity or liquid fuels for transportation.

Before World War II, forages fueled agriculture even in industrialized countries. In 1920, the 27 million horses and draft animals in the United States, fed mainly hay and pasture (i.e., herbaceous biomass), pulled plows and transported goods and people (Vogel, 1996). By the 1950s, agriculture was largely mechanized, and fossil fuels provided nearly all of the energy inputs. In 1995, agriculture accounted for 3% of the global primary energy use (Price et al., 1998). The lignocellulose in forage crops represents a vast and renewable source of biomass feedstock for conversion into liquid fuels, thermochemical products, and other energy-related end products (Fig. 41.1) (McLaughlin et al., 2002). With new technologies and processes for biomass production and conversion nearing commercial reality (De La Torre Ugarte et al., 2003), forages could once again fuel agriculture.

In this chapter, we address the use of forage crops for the production of these alternative products and how management practices may differ from traditional forage uses. The economics of using forage feedstocks and the effects on environmental aspects are considered briefly.

Forage Species and Cultivars for Biofuels

Some of the most extensively studied species for biomass feedstock production include switchgrass, *Miscanthus* spp., sugarcane, elephantgrass, reed canarygrass, and alfalfa (Table 41.1).

Switchgrass

Switchgrass is considered a model herbaceous energy crop because of its high productivity across many environments, suitability for marginal and erosive land, relatively low water and nutrient requirements, and positive environmental benefits (Sanderson et al., 1996; McLaughlin

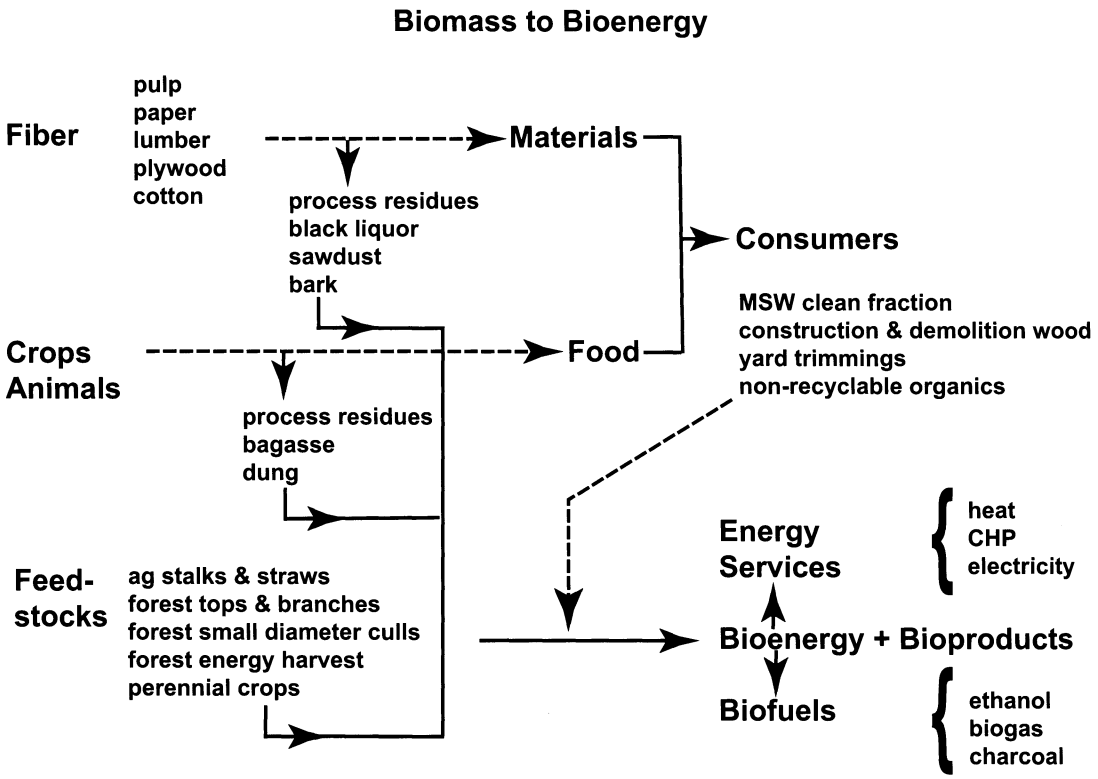

FIG. 41.1. Illustration of the biorefinery concept, that is, the use and conversion of biomass feedstock to energy and industrial products. (MSW = municipal solid waste.) (Adapted from the US Dept. of Energy [Online]; available at http://bioenergy.ornl.gov (verified 30 March 2004.)

Table 41.1. Biomass yields of selected perennial forages at several locations in the United States and Europe

Species	Location	Yield range Low	High	Average	Site-years	Reference
			(Mg ha^{-1})		*(no.)*	
Bermudagrass	Alabama	1.0	9.0	6.5	16	Bransby et al., 1989
Bermudagrass	Georgia	9.2	24.9	17.6	12	Bouton, 2002
Bahiagrass	Georgia	2.1	18.8	11.0	12	Bouton, 2002
Elephantgrass	Georgia	13.3	41.6	27.8	12	Bouton, 2002
Elephantgrass	Florida	19.0	31.0	—	4	Prine et al., 1995
Saccharcum spp.	Florida	27.0	37.0	—	4	Prine et al. 1995
Eastern gamagrass	New York	4.2	8.8	—	30	Fick et al., 1994
Alfalfa	Minnesota	8.4	12.7	11.2	9	Sheaffer et al., 2000
Reed canarygrass	Switzerland	11.0	19.0	14.2	6	El Bassam, 1998
Timothy	Switzerland	11.0	18.0	15.6	6	El Bassam, 1998

Table 41.2. Yields of switchgrass at several sites in the United States, Canada, and England

Location	Cultivars		N rate	Site-years	Harvests	Reference
	Alamo	Cave-in-Rock				
	(Mg ha^{-1})		*(kg ha^{-1})*	*(no.)*	*(no. yr^{-1})*	
Alabama	27.1	13.8	110	5	1	McLaughlin et al., 1999
Indiana	—	14.4	112	2	2	Hopkins et al., 1995
Iowa	—	14.3	112	2	2	Hopkins et al, 1995
Iowa	12.1	9.3	112	4	1	Lemus et al., 2002
Georgia	16.2	9.2	—	12	1	Bouton, 2002
Mississippi	11.6	6.8	73	3	2–3	Lang et al., 2003
Nebraska	—	13.0	112	2	2	Hopkins et al., 1995
New York	—	4–11.3	30–135	—	1	Fick et al., 1994
Pennsylvania	—	10.0	84	—	1	Stout, 1994
Mid-Atlantic USA[1]	15.3[2]	11.5[3]	50	64	1	Parrish et al., 2002
South Dakota	—	3.8	112	4	1	Casler and Boe, 2003
Texas	12.7	4.6	67–34	6	1	Sanderson et al., 1999b
Wisconsin	—	14.3	112	4	1	Casler and Boe, 2003
Montreal, Canada	—	12.2	50	2	1	Madakadze et al., 1998
Rothamsted, England	13.4[4]	11.8	60	4	1	Christian et al., 2002

[1]Includes sites in VA, WV, KY, and NC.
[2]Average of Alamo and 'Kanlow' cultivars.
[3]Average of Cave-in-Rock and 'Shelter' cultivars.
[4]Kanlow was the cultivar used.

et al., 2002). 'Alamo' is one of the best-adapted cultivars for the southern United States, and 'Cave-in-Rock' is one of the better-adapted cultivars for the mid-Atlantic, Northeast, and Midwest regions (Sanderson et al., 1999b; McLaughlin et al., 1999) (Table 41.2). Switchgrass also performed well as a biomass crop in European field trials (Elbersen et al., 2000). Research continues on genetic improvement of switchgrass biomass yields and environmental benefits such as increases in soil organic-C (McLaughlin et al., 2002).

Miscanthus

European bioenergy research focused on *Miscanthus* species to supply biomass feedstock for combustion steam plants (Clifton-Brown et al., 2001). The genus *Miscanthus* includes C_4 rhizomatous grasses native to Asia, which are winter hardy in temperate areas of Europe and have relatively high biomass production (Table 41.3). In most of Europe, *Miscanthus* grows from April until November; however, harvest of the previous year's biomass in February or March is recommended because moisture content and alkali elements in the standing biomass are reduced (El-Bassam, 1998).

Field-plot trials across Europe indicated significant genotype × environment interactions for biomass yields of *Miscanthus*. Yields as high as 41 Mg ha^{-1} were obtained under irrigation in the warmer climate of Portugal.

Table 41.3. Biomass yields of *Miscanthus* for 3 yr at several European locations

Location	Low	High	Average
		(Mg ha^{-1})	
Denmark	1.4	18.2	9.1
England	0.9	18.7	8.5
Germany	3.0	29.1	13.4
Sweden	0.4	24.7	11.5
Portugal	7.5	40.9	25.2

Source: Data from Clifton-Brown et al., 2001.

M. giganteus hybrids performed better in mid- and southern Europe (Germany southward), whereas *M. sinensis* hybrids performed better in northern Europe (Clifton-Brown et al., 2001). In general, *M. giganteus* and *M. sacchariflorus* will not do well where winter soil temperatures fall below −3°C at a 5-cm soil depth.

Reed Canarygrass.

Other European research on bioenergy crops has identified reed canarygrass as a highly productive perennial for northern Europe (El Bassam, 1998; Lewandowski et al., 2003a) (Table 41.1). Reed canarygrass is a C_3 grass that is well adapted to temperate areas and does well on wet soils. Similar to switchgrass, reed canarygrass can be slow to establish, and yields are low in the seeding year. In North America, however, some groups consider reed canarygrass an invasive species, especially in native wetlands.

Elephantgrass

The tropical climate of the lower southern United States, Puerto Rico, and Hawaii favors the tall perennial tropical grasses such as elephantgrass. The long, warm growing season and high rainfall in these areas provide conditions for high yields ranging from 13 to 42 Mg ha^{-1} dry matter (Prine et al., 1995; Bouton, 2002) (Table 41.1). This C_4 grass is best adapted to USDA plant hardiness zones 8 and 9 (see map of hardiness zones in Chap. 6).

Alfalfa

An innovative system of using alfalfa for both biomass feedstock and a high-quality animal feed was developed in Minnesota in the 1990s (Martin, 1998). The system separated the leaves for high-value, high-protein feed and used the lower-quality stems, which are high in lignocellulose, in an integrated gasification combined cycle system to produce electricity. The proposed system recommended two-cut harvest management to optimize economics, yield of stem and leaf, and wildlife habitat. Genetic selection efforts concentrated on lines developed for stiff stems with increased internode length to be grown under infrequent harvest (Lamb et al., 2003).

Other Species

Several other perennial grasses, some not necessarily forage grasses, have been suggested as potential energy plants, including bermudagrass, timothy, brown beetle grass, alemangrass, common reed, cordgrass (*Spartina* spp.), giant reed, and coastal panicgrass (El Bassam, 1998). Each has unique growth and adaptation characteristics that gives them potential as bioenergy crops.

Management for Bioenergy Cropping

An advantage of using existing forages as bioenergy crops is that farmers are familiar with their agronomic management and already have the machinery, technology, and infrastructure needed to establish, manage, harvest, store, and transport them. Forage crops offer additional flexibility in management, because they can be used for biomass or forage and the land can be returned to other uses or put into crop rotation.

Fertility Management

Because manufacture of N fertilizer requires a large amount of energy (40 MJ of natural gas per kilogram of NH_3), its efficient use is paramount in bioenergy crop production. Thus, the use of a N-fixing crop, such as alfalfa, offers advantages in terms of N fertilizer use.

Traditional fertilizer recommendations for forage production may not apply to production of bioenergy feedstock. For example, research on N fertilization of switchgrass for biomass feedstock indicates variable responses depending on management and soils. On low organic matter, low fertility soils in Texas, Alamo switchgrass showed a strong response to N up to 168 kg ha^{-1} (Muir et al., 2001). Recommendations of soil fertility for switchgrass management in the mid-Atlantic region of the United States include maintain pH above 5.0; apply 50 kg P ha^{-1} when soil test P is low; apply 100 kg K ha^{-1} when soil test K is low to medium; apply 50 kg N ha^{-1} in spring for a one-cut harvest system or 50 kg in spring and 50 kg after the first harvest for a two-cut system (Parrish et al., 2002). In the Midwest United States, switchgrass required 10–12 kg ha^{-1} of N for each Mg of yield (Vogel et al., 2002).

Warm-season perennial grasses internally recycle N from the aboveground shoots to the crown and roots in the fall for use in overwintering and regrowth the following spring (Clark, 1977). This mechanism enables an efficient use and reuse of N by the plant. About 18% of the annual N demand of big bluestem and indiangrass on native prairie comes from internal reserves (McKendrick et al., 1975). There is some evidence of an internal recycling mechanism for N in switchgrass (Parrish et al., 1995) and reed canarygrass (Partala et al., 2001) grown for biomass feedstock. Long-term data are needed to clarify when N recycling occurs, how much recycles, and how it contributes to the N economy of a biomass energy crop.

Harvest Management

Because traditional forage quality attributes differ from those of biomass feedstock quality, harvest management for biomass feedstock emphasizes yield and persistence. For example, proposed management of alfalfa as a biomass energy crop includes only two harvests, whereas traditional forage management involves harvests at bud to early flower stages to optimize yield, nutritive value, and persistence (Lamb et al., 2003). A diversified farming operation may require more flexibility in harvest management to satisfy multiple goals, such as providing quality forage for livestock as well as biomass. Producers managing stands that are dedicated to production of biomass feedstock may want harvest flexibility to respond to potential fluctuations in future feedstock markets.

Generally, bioenergy crop production seeks to maximize the concentration of lignocellulose and to minimize concentrations of N and minerals in the feedstock at harvest time. Harvest recommendations for switchgrass for maximum biomass yields include a single fall harvest in the south central United States (Sanderson et al., 1999a), north central United States (Casler and Boe, 2003), and Quebec, Canada (Madakadze et al., 1999). Although two

Table 41.4. Biomass feedstock quality at fall and spring harvests of two grasses

			Miscanthus[2]			
	Reed canarygrass[1]		December		February	
Constituent	Summer	Spring	Leaf	Stem	Leaf	Stem
Energy (GJ kg^{-1})	17.9	17.6	18.5	18.9	18.9	19.0
Ash (g kg^{-1})	64.0	56.0	25.8	24.7	15.7	19.2
N (g kg^{-1})	13.3	8.8	1.9	4.5	1.9	7.6
S (g kg^{-1})	1.7	0.9	1.1	1.1	1.0	1.1
Cl (g kg^{-1})	5.6	0.9	4.5	0.8	1.0	1.1
K (g kg^{-1})	12.3	2.7	15.0	4.3	8.3	6.6
Ash fusion temp (°C)	1074	1404	—	—	—	—

[1]Data from Burvall, 1997.
[2]Data from Lewandowski and Kircherer, 1997.

harvests per year may be needed for maximum production of upland switchgrass cultivars in the mid-Atlantic and southeastern United States, this may not be economical (Parrish et al., 2002). Delaying a single harvest until late winter or early spring reduces the concentrations of N, alkali elements, and moisture in reed canarygrass and *Miscanthus* at harvest (Lewandowski and Kicherer, 1997; Burvall, 1997) (Table 41.4) and may be appropriate for biomass crops in some instances. Delayed harvest, however, reduced biomass yields of *Miscanthus* by 35% (Lewandowski et al., 2003b). Developmental stages of full panicle emergence to post-anthesis were recommended as the optimal time to harvest switchgrass in the midwestern United States (Vogel et al., 2002). Compared with an August harvest, delaying harvest until after frost resulted in yield losses of 1–2 Mg ha^{-1} in the Midwest.

Use of Conservation Lands for Feedstock Production

Land in the Conservation Reserve Program (CRP) has been suggested as a potential, readily available resource for biomass feedstock production in the United States (De La Torre Ugarte et al., 2003). The CRP, authorized by the Food Security Act of 1985, pays owners and operators to set aside environmentally sensitive lands. Canada has a similar program called Greencover Canada (Agriculture and Agrifood Canada, 2003). The goal of the CRP is to remove land from crop production and plant long-term resource-conserving vegetation cover to prevent soil erosion, improve water quality, and enhance wildlife habitat. Assessing the quality of the feedstock and developing management systems consistent with maintaining the environmental benefits of the CRP are key considerations in its potential use for bioenergy.

De La Torre Ugarte et al. (2003) identified 6.8 million of the 12.1 million ha of CRP land (1998 data) as being potentially available for biomass feedstock production. In 2003 there were 14 million ha of CRP land concentrated mainly in the central plains and midwestern United States (USDA Farm Service Agency, 2004). Of the total CRP area, 1.4 million ha were planted to CP-1 mixtures (introduced grasses), 2.6 million ha were planted to CP-2 mixtures (native grasses), and 6.2 million ha were classified as CP-10 (established grass). The remaining 3.8 million ha were in trees, wildlife habitat, or other conservation practices.

Little is known about the plant composition or amount of biomass produced on CRP grasslands. A survey of CRP lands in Minnesota established according to the NRCS CP-2 recommendations (use of native grasses and no herbicides) revealed that switchgrass was planted in 100% of the CP-2 fields (Jewett et al., 1996). Switchgrass persisted on 94% of the fields planted and generally exceeded 50% ground cover on all sites after 6–8 yr. In the northeastern United States, a 2-yr survey identified more than 280 herbaceous plant species on CRP and other lands used for conservation purposes. The average species richness was 34 species per 0.1 ha, and average standing biomass in autumn was 6.6 Mg ha^{-1} (Adler et al., 2003).

Maintaining the environmental benefits of the CRP is a concern when considering its potential for bioenergy production. This would include maintaining a perennial vegetative cover to prevent soil erosion and judiciously using fertilizers to obtain economic yields and not compromise water quality. Other management considerations for the use of CRP lands for biofuels in the future would include harvest management consistent with maintaining wildlife habitat. In 2003, a new interim rule was adopted that allowed managed haying or grazing on CRP-l and 1 out of every 3 yr after the cover is fully established. Managed haying or grazing is not allowed during the primary nesting or brood-rearing season. In addition, a payment reduction of 25% is assessed for the acreage harvested (Federal Register, 2003).

Economics, Environment, and Energy Balance

Currently, biofuels cost more than fossil fuels. In 1999, the unit-energy costs of a gigajoule (GJ) for various fuels were \$2.82 GJ^{-1} for oil; \$0.78 GJ^{-1} for coal; and \$1.76 GJ^{-1} for natural gas. Estimates of unit-energy costs for biofuels range from \$1.83 to \$2.44 GJ^{-1} (Walsh et al., 2003). Biomass yield, harvest and transport costs, conversion efficiency, and cost of fossil fuel used to produce the biofuel determine the economics of bioenergy production and vary among regions of the United States. The value of environmental benefits of bioenergy crops, however, may offset the price differential between biofuels and fossil fuels (McLaughlin et al., 2002).

Environment

The environmental benefits of bioenergy crops include increasing soil quality, reducing losses of soil nutrients (Kort et al., 1998), protecting riparian zones (Schnabel, 2000), recycling nutrients from sewage sludge and livestock manure (Reed et al., 2002; Sanderson et al., 2001), and sequestering soil C (Romm et al., 1998), among other benefits.

Biomass-derived fuels, in contrast with fossil fuels, have a near-zero balance of net-C exchange with the atmosphere, depending on the amount of fertilizer and fossil fuel used in production and processing (McLaughlin et al., 2002). Several studies have reported increases in soil organic C under switchgrass grown as a biomass feedstock in North America (Garten and Wullschleger, 1999; Zan et al., 2001; Tolbert et al., 2002). The large amount and deep distribution of root biomass in the soil beneath perennial energy crops may enhance C sequestration because roots persist longer at greater depths and C in deep roots may be more stable than C in biomass near the soil surface (Reeder et al., 2000).

Potential benefits from C sequestration under biomass energy crops may depend on the cropping system used or replaced. In the southeastern United States, switchgrass grown for biomass accumulated more total C in aboveground biomass and in soil than cotton or corn but not as much as bahiagrass (Bransby et al., 1998). Soil organic-C concentrations and inventory under switchgrass were no different than that beneath tall fescue or pasture in the mid-South (Garten and Wullschleger, 1999). Thus, C benefits may accrue if switchgrass replaces annual row crops but not if it replaces other perennial sod-forming grasses.

Human health may benefit from a greater reliance on renewable fuels made from forage crops. Currently, methyl-tertiary-butyl-ether (MTBE) is the common oxygenate additive to gasoline; however, MTBE has great potential to contaminate groundwater and poses a human health risk. Ethyl-tertiary-butyl-ether (ETBE) can be substituted for MTBE in gasoline to increase octane and lower or alter the emissions from vehicles and is less toxic than MTBE (Brown, 2003). The methanol used to make MTBE is generated from fossil fuel sources, whereas ethanol for ETBE can be made from renewable sources such as forage biomass. The potential reduction in air pollution resulting from the reduced emissions may improve human health. Similarly, the reduced use of agrichemicals and improvements in water quality resulting from increased use of perennial biomass energy crops have human health implications (Brown, 2003).

Energy Balance

Life cycle analysis or assessment has been used to evaluate the environmental impacts of products through quantifying their energy and material flows at all stages (Keoleian and Menerey, 1993). Three key elements in conducting a life cycle assessment of biofuels are the energy balance, N cycles, and C cycles. The energy balance for switchgrass production considers the energy content of the biomass minus the fossil energy used in production (i.e., the net energy production from the system). Biomass can be directly combusted, or the cellulose fraction can be converted to ethanol and the lignin fraction combusted. Producing ethanol from switchgrass results in an energy ratio (ratio of energy output vs. energy input; values greater than 1 imply energy output greater than input) of about 3.3 compared with 1.2 from corn grain (McLaughlin and Walsh, 1998). This is because the corn stover is not included in the energy balance. Return of corn stover to the soil is needed to maintain soil quality (Wilhelm et al., 2004).

An example of the energy input for an alfalfa biomass energy crop rotation is seen in Table 41.5. The dedicated feedstock production system produced alfalfa hay for stems to be converted to electricity through gasification and for leaves to provide animal protein supplement. The specific crop rotation was 4 yr of alfalfa, 2 yr of corn, and 1 yr of soybean. Energy inputs were about 40% less ha^{-1} for the dedicated feedstock system compared with the corn–soybean rotation. Energy output was 3300 GJ Mg^{-1}, such that the energy ratio of the production system was 3 (Martin, 1998) (Table 41.6).

The N cycle has a significant impact on the energy balance and production of greenhouse gases. The fossil fuel energy required to produce N used in biofuel production can account for a significant portion of the total system energy requirements. Thus, reducing the amount of fertilizer N needed can significantly increase the energy balance (net production) of the system. Perennial crops such as switchgrass have lower requirements for N than an annual crop such as corn, thereby reducing the fossil fuel energy requirement. Lower N use also reduces the emission of NO_x, a potent greenhouse gas.

Table 41.5. Energy inputs for two 14-yr crop rotations

Inputs	Dedicated feedstock system[1]	Corn-soybean rotation
	(GJ ha^{-1})	
Machinery and fuel	5.9	6.5
Fertilizer	6.1	10.9
Seeds	2.9	4.5
Chemicals	0.7	0.5
Drying	2.4	4.3
Transport	0.6	0.6
Total	18.6	27.3

Source: Martin, 1998.

[1]Crop rotation included two 7-yr rotations, each consisting of 4 yr of alfalfa followed by 2 yr of corn and 1 yr of soybean.

Table 41.6. Energy balance of alfalfa production

	GJ Mg^{-1}
Inputs	
Farm production to storage	656
Transportation to conversion	216
Drying from 15% to 10% moisture	336
Fractionation	234
Total inputs	1442
Output	
Feed (energy equivalent to soybean meal)	1097
Electricity	3296

Source: Martin, 1998.

Biofuel production should recapture all of the C emitted during fuel combustion through uptake of CO_2 by photosynthesis during crop growth if the amount produced and combusted is the same. Carbon closure, the percentage of C recycled during production and consumption of biofuels, ranges from slightly less than 100% to significantly greater than 100%, where a 100% closure represents a zero net C process. The large variation in C closure results from the natural variation in capacity of soils to sequester C and the degree to which particular soils have reached their C saturation capacity. The rate of C sequestration decreases as soils increase in C content and approach saturation (Six et al., 2002) (Fig. 41.2).

Bioenergy Conversion

In contrast with petroleum refineries, which use oil as the feedstock, a biorefinery converts biomass feedstock into a number of high-value chemicals and energy. Optimally, the biorefinery also finds a use for by-products to provide another income source and to minimize wastes and emissions (Elliott, 2004).

Conversion Methods

The three broad categories of converting lignocellulosic biomass (plant tissue) to different energy or chemical end products include biochemical processes, thermochemical methods, or direct combustion (McKendry, 2002b). To produce ethanol, plant cell walls are chemically or biochemically digested to simple fermentable sugars such as glucose. Typically, the biomass is pretreated to reduce feedstock size, to facilitate the breakdown of hemicellulose to simple sugars, and to expose the cellulose to allow greater access by enzymes. The feedstock is then hydrolyzed and fermented before the fermented product is distilled to obtain ethanol (Fig. 41.3) (Brown, 2003). The lignin remaining after separation from sugars can be used to fuel the process (Sun and Cheng, 2002). Approximately 330 L of ethanol can be produced from 1 Mg of a dry biomass such as switchgrass.

Thermochemical conversion processes include pyrolysis, gasification, and liquefaction (McKendry, 2002b), which can be used to convert biomass to methanol, synthesis gas, and pyrolysis oils. Gasification converts all carbon to a synthetic gas, mainly hydrogen (H_2) and carbon monoxide (CO), which is then burned or converted chemically to other products.

Larger-scale direct combustion includes processes where herbaceous biomass is burned in industrial-sized boilers to produce steam and generate electricity (Brown, 2003). The alkali minerals and moisture in biomass cause problems, such as fouling of boilers, in direct combustion systems. Mixing biomass and coal together for combustion, known as co-firing, can help reduce sulfur emissions, allow for flexibility in using different fuels, and can alleviate some problems of biomass combustion associated with ash and minerals fouling the combustor (Sami et al., 2001).

Chemical Composition and Fuel Quality of Feedstock

The efficiency and end products of the various conversion processes depend on the chemical composition of the biomass. Biomass contains higher concentrations of inorganic elements such as K and Ca compared with fossil fuels such as coal (Table 41.7). High concentrations of alkali metals enhance the formation of fusible ash, which causes slagging and fouling of boilers used for direct combustion (Miles et al., 1996) and disrupts fluidized bed combustion systems (Zeven-Onderwater et al., 2001). Feedstocks high in N and ash reduce hydrocarbon yields during thermochemical conversion. Pyrolysis oils ob-

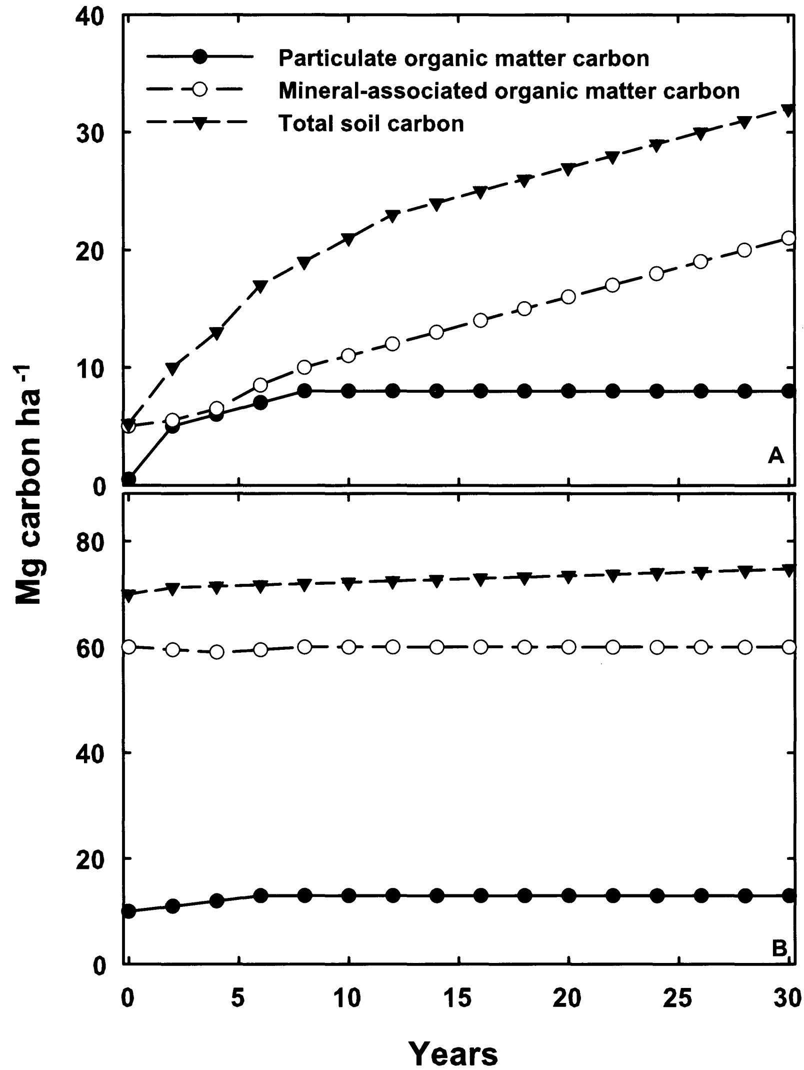

FIG. 41.2. Predicted changes in different soil C fractions (to a 1-m depth) under switchgrass grown on *(A)* soil with low initial soil C stock in a warm climate and *(B)* soil with a high initial soil C stock in a cool climate. (Adapted from McLaughlin et al., 2002.).

tained from feedstock having high ash concentrations are higher in Cl and K. Burning these pyrolysis oils corrodes turbines used to generate electricity (McKendry, 2002a, 2002b). Total ash concentrations in forages usually decrease as forages mature (Sanderson and Wolf, 1995). Thus, harvesting forages at late maturity stages would minimize the concentrations of inorganic elements in the feedstock.

Combustion of lignin from forage crops used for biomass contributes energy to the thermochemical conversion process (Sun and Cheng, 2002). Lignin, however, reduces the availability of cellulose and other structural polysaccharides and reduces ethanol yields during the biochemical process of fermentation (Sun and Cheng, 2002). Pretreatment of lignocellulose with anhydrous ammonia under pressure or with a steam explosion may increase the conversion efficiency by physically disrupting the fiber.

Modern plant-breeding and molecular biology techniques can be used to improve the chemical composition of forages for use as biomass and co-products (Vogel and Jung, 2001). This technology will enable plant breeders,

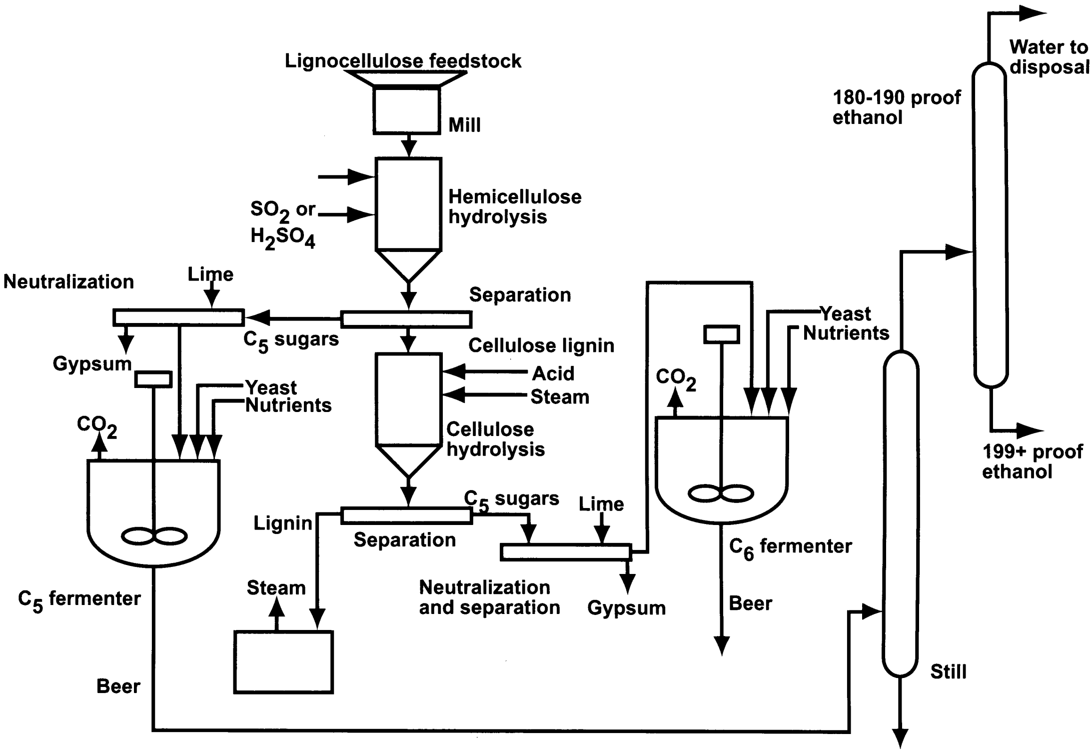

Fig. 41.3. Schematic of the conversion of lignocellulosic biomass to ethanol via the dilute acid hydrolysis method. (Adapted from Brown, 2003.)

Table 41.7. Comparison of the chemical composition of selected biomass feedstocks

Constituent	Critical limit[1]	Reed canarygrass[2]	Switchgrass[3]	*Miscanthus*[4]	Hybrid poplar[5]	Coal[5]
Energy (GJ Mg)	—	17.9	17–19	17–19	19	27–30
Cellulose (g kg^{-1})	—	—	361	—	420–560	—
Hemicellulose (g kg^{-1})	—	—	316	—	180–250	—
Lignin (ADL) (g kg^{-1})	—	—	61	—	210–230	—
N (g kg^{-1})	10	13.3	5.6	—	—	11.6
Ash (g kg^{-1})	—	64.0	57	45–58	5–15	82.0
K (g kg^{-1})	—	12.3	5	5–10	0.3	0.2
S (g kg^{-1})	< 3	1.7	1.2	1.2	0.3	5.5
Cl (g kg^{-1})	2	5.6	1.4	—	—	0.2
Ash fusion temp (°C)	> 1150	1074	1100	1090	1350	1300

[1]Critical limits from Lewandowski and Kircherer, 1997.
[2] Reed canarygrass data from Burvall, 1997.
[3] Switchgrass data from Brummer et al., 2002.
[4]*Miscanthus* data from Lewandowski and Kircherer, 1997.
[5]Hybrid poplar and coal data from Scurlock, 2000.

conversion chemists, and engineers to tailor bioenergy crops for specific conversion processes, higher energy yields, and development of new co-products.

Other Industrial Products from Forages

Wet fractionation of forage crops, such as alfalfa, adds value to biomass through the spin-off of co-products before processing for energy. The fractionation process consists of expressing high-value juice from fresh herbage, leaving a reduced-moisture fibrous fraction high in cell wall constituents (cellulose, hemicellulose, and lignin). The fiber is suitable for combustion, gasification, or enzymatic hydrolysis and fermentation to ethanol or organic acids (Koegel and Straub, 1996).

The juice fraction from the wet fractionation of alfalfa contains 25%–30% of the dry matter in the original herbage, depending on the severity of processing. The liquid fraction is occasionally used in its entirety, either fresh or preserved, as part of animal rations, including those of nonruminants such as swine and poultry (Jorgensen and Koegel, 1988). More frequently, however, the liquid is further divided into a protein-rich fraction containing 40%–60% crude protein on a dry matter basis and a deproteinized juice with 7% or less dry matter and negligible true protein content. The protein fraction can be used to produce both food-grade and feed-grade protein concentrates.

Other high-value juice products include soluble protein suitable for human food, xanthophyll concentrates for use in poultry rations, plant and animal growth stimulants, cosmetic substances, and pharmaceuticals. Additional industrial products from alfalfa include lactic acid, used as a food ingredient and preservative (Sreenath et al., 2001), enzymes such as phytase, cellulase, and alpha-amylase, and biodegradable plastics (Saruul et al., 2000).

Alfalfa can be genetically modified to produce industrially valuable substances, especially enzymes. Fields of alfalfa could thus become "bioreactors" or "enzyme factories," with the target enzyme recovered from the juice. To date, transgenic alfalfa cultivars have been produced that contain Mn-dependent lignin peroxidase for biopulping, alpha-amylase for converting starch to sugar, phytase for releasing P from phytic acid, and cellulase for the conversion of cellulose to sugars.

Research on the fermentation of saccharified (complex polysaccharides in lignocellulose broken down to simple sugars through hydrolysis) alfalfa to ethanol and lactic acid indicates better return from lactic acid because of its higher yield and higher unit price. Liquid hot water pretreatment of alfalfa fiber has been shown to result in an 80% yield of lactic acid; however, the economic advantage of the pretreatment is still unclear because it requires considerable capital and operating cost.

The Minnesota Valley Alfalfa Producers produced a leaf meal from alfalfa biomass by sifting ground alfalfa through various screens to separate leaves from stems. The stems were used for biofuel. The leaf meal contained from 250 to 290 g kg^{-1} crude protein. Animal trials demonstrated that the alfalfa leaf meal was a suitable substitute for hay and soybean meal in diets of lactating dairy cows (DiCostanzo et al., 1999). As a component (12% or less of diet dry matter) of starter diets for young calves, alfalfa leaf meal has the potential to enhance intake and gain. At greater proportions in the diet, alfalfa leaf meal may reduce intake in young calves.

Fermented alfalfa fiber may be used in adhesives. A patent invention has been recorded to make an adhesive composition useful for producing wood products. Fermentation of pure alfalfa cellulose with a preparation of *Ruminococus albus* results in an adhesive substance containing adherent microbial cells and glycocalyx. This residue finds particular application as a replacement for a significant amount of phenol-formadehyde resin commonly used in the preparation of plywood and other wood products (Weimer, 2003).

Lignocellulose from reed canarygrass, switchgrass, and *Miscanthus* could serve as a supplement to wood as a raw feedstock for papermaking pulps (Fox et al., 1999; Finell et al., 2002). The cellular composition of herbaceous biomass, however, differs from wood and requires extra processing, including a pretreatment called *dry fractionation* to remove nonfibrous cells and isolate the fibrous stem material. The relatively high mineral concentrations in herbaceous biomass also hinder the pulping process.

Summary

Forages have great potential as sustainable feedstocks for energy and industrial products. Estimates are that switchgrass could be grown profitably on 17 million ha of land (including current CRP land) in the United States if the farm gate price were \$2.44 GJ^{-1} of energy. This could potentially offset up to 253 million barrels of oil (3.7% of the annual oil consumption in the United States) or up to 7.3% of the electricity produced in the United States (Walsh et al., 2003). The principal limitation to increased use of forages for biomass is their high cost relative to fossil sources of carbon such as coal and oil. Valuing the environmental benefits of forages as renewable industrial crops, such as reduced soil erosion, C sequestration, and reduced production inputs, would place them on par with fossil carbon sources.

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